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13. ABSTRACT *(Maximum 200 words)*

These models explore interactions among (a) Weapon systems, (b) Intelligence, Surveillance, and Reconnaissance (ISR) capacity, accuracy, and timeliness, (c) Concepts of Operation, and (d) Scenarios. These interactions allow us to estimate the sensitivity of top-level Measures of Effectiveness (MOEs such as BLUE losses and time taken to achieve BLUE's operational objective) to factors such as

Improved weapons Pk at longer range; Improved ISR/Battle Damage Assessment (BDA) capability; RED ISR/BDA deception tactics; Improved ISR/BDA counter-deception capabilities; Alternative concepts of operation (as defined by parameters such as number of targets attacked per wave, attacker weapon mix, etc.); Changes in scenario parameters (e.g., total numbers of targets and non-targets).

The effects of imperfect, non-instantaneous ISR/BDA on combat attrition are captured by a set of target states which combine BLUE perception, ground truth, and recent target history. Target state populations after the (n+1)st wave are computed from target state populations after the nth wave via functional dependencies involving the attrition, ISR/BDA, OPS concept, and scenario models used. By tracking these target state populations with time, one can unravel the chains of cause-and-effect that lead to the (sometimes counterintuitive) sensitivities of MOEs to the various parameters mentioned earlier.

14. SUBJECT TERMS

MORS, Combal Models, ISR, BDA, Intelligence, Surveillance, Reconnaissance, Battle Damage Assessment, Air Attacks vs. Ground Targets

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Air Attacks vs. Fixed, Defended Ground Targets:

Combat Models with Imperfect, Non-Instantaneous ISR/BDA

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June 20, 1996

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Objectives

The purpose of this exploratory model was to begin getting a better understanding of the interaction between combat and ISR/BDA. For this reason a very simple scenario was chosen, i.e., air attacks against fixed ground targets. This allowed us to focus exclusively on the capability of ISR/BDA to distinguish a target from a non-target or dead target, without having to consider other ISR dimensions such as age of data or target tracking. To simplify the problem even further we deliberately used an expected-value approach, rather than attempting to take stochastic effects into account. We wanted to learn as much as possible regarding assumptions, cause-and-effect, target state structure, BLUE perception vs. ground truth, and their impacts on combat outcomes, from this simple model before starting to introduce additional effects. And of course we wanted to understand the extent to which the insights gained from this model can be extrapolated to more complex situations.

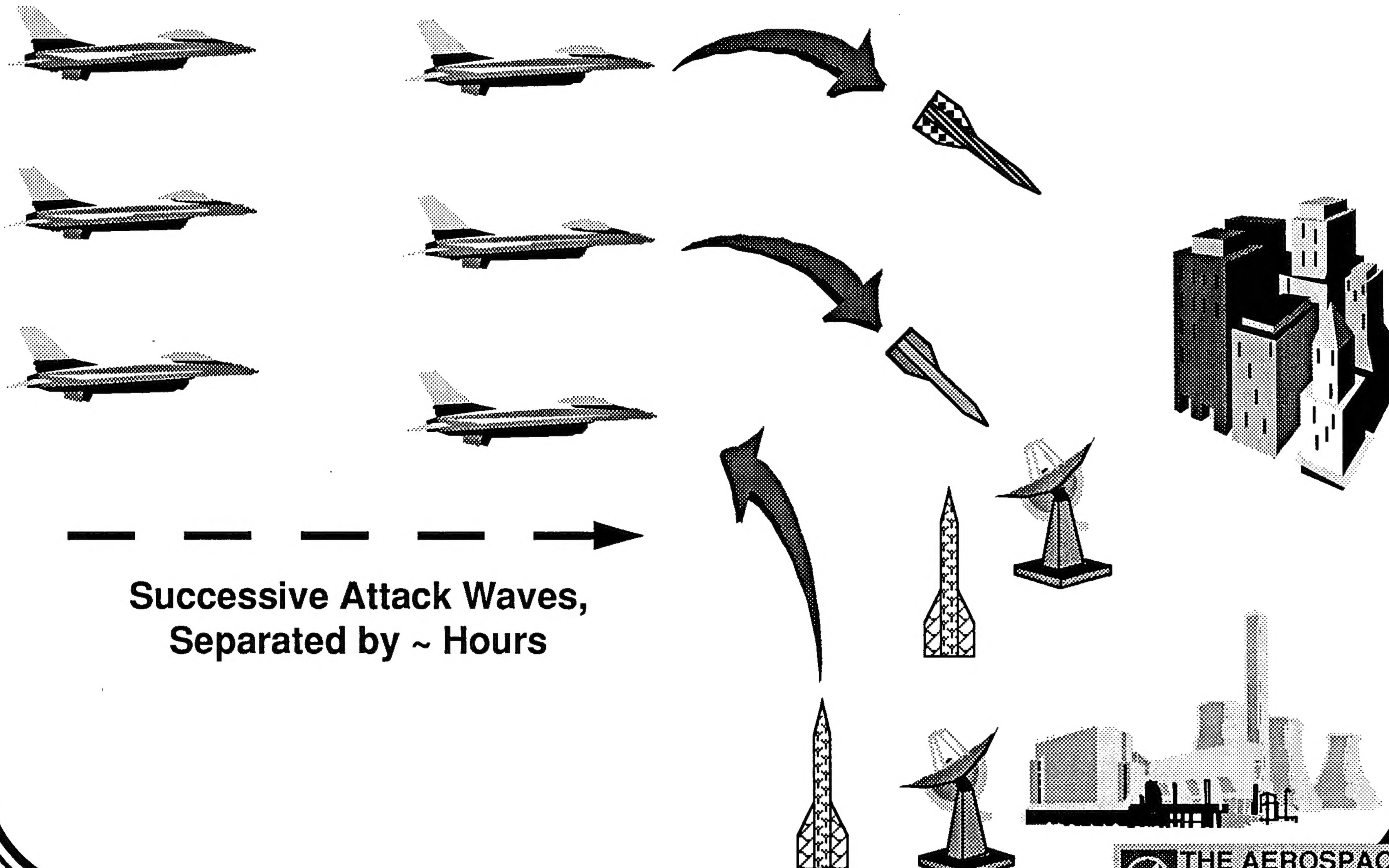
Objectives

- Exploratory Modeling to begin getting insight into impact of ISR on combat outcomes; Heavy parametric flavor; Walk before run:
  - Fixed Ground Targets -> No age of data, No tracking
  - Focus on impacts of False Positives, False Negatives
- No stochastic effects. Use probabilities only to compute expected values
- Which conclusions make sense? Which don't? What important effects are not captured? What kinds of subtleties arise in even simple models?
- Identify/Understand chains of cause and effect that link inputs and assumptions to outputs
- What kind of target state structure is needed to capture the impact of ISR on combat?
- In what ways do discrepancies between BLUE's perceptions and the ground truth impact combat outcomes?

Air Attacks Against fixed Defended Ground Targets

The scenario analyzed involves successive waves of attackers striking fixed ground targets that are defended. The defenders might be SAM sites, or AA batteries, for example. BLUE's objective is to kill some fraction, say 50%, of all the RED targets.

Air Attacks Against Fixed Defended Ground Targets



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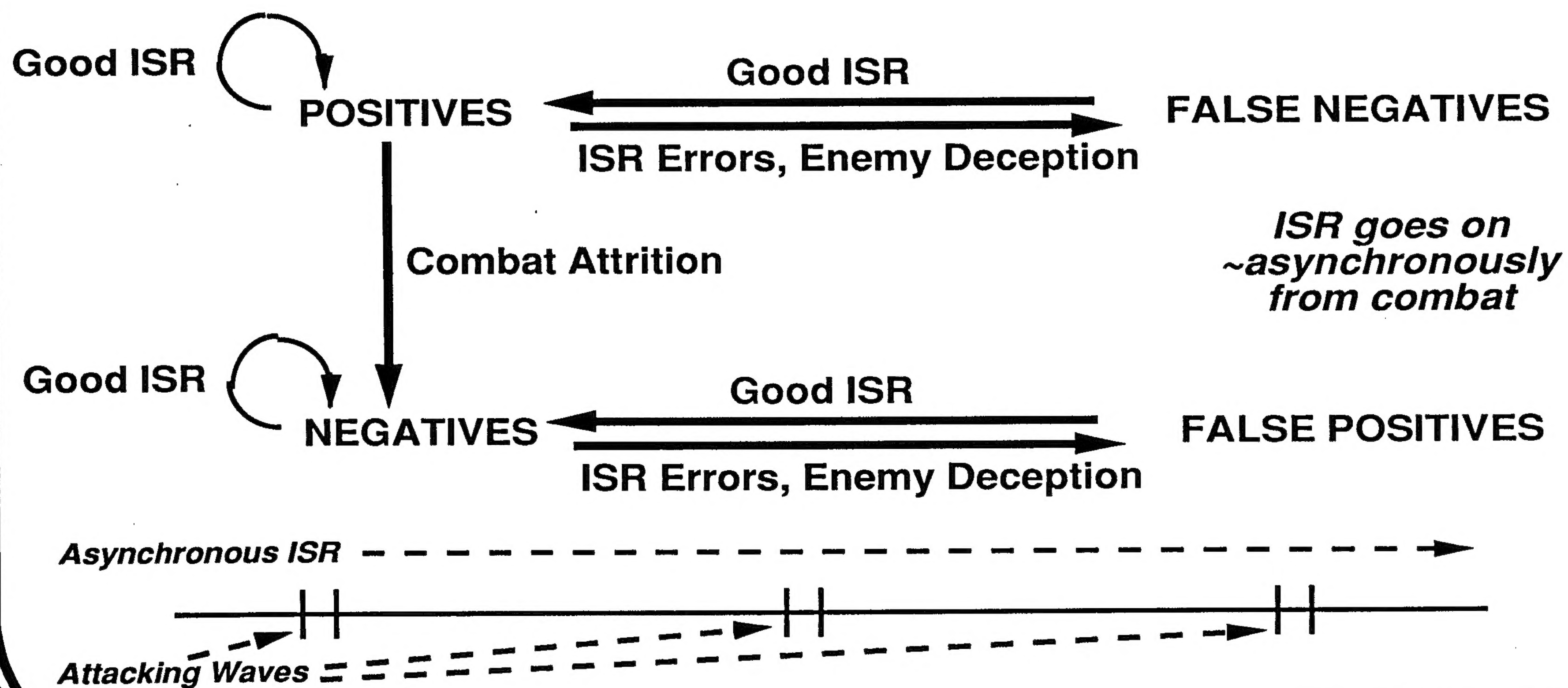
Essential Features Modeled

At the same time that BLUE is sending out successive waves to attack RED, there is ISR/BDA going on more or less continuously and asynchronously from the combat activities. Positives are things BLUE wants to kill, and Negatives are things he's not interested in. False Positives and False Negatives arise when BLUE mistakes a Positive for a Negative, or vice-versa. ISR capability in this model is defined by how well BLUE can distinguish Positives from Negatives, and how quickly it can do this. ISR/BDA will degrade due to deception by the enemy, or due to the extent to which Positives are mistaken for Negatives (or vice-versa).

Essential Features Modeled

- BLUE Attacks RED in waves, usually separated by hours
  - Each BLUE wave attacks only a subset of RED (i.e., M targets)
  - RED DEFENDERS shoot at BLUE and vice-versa
- Attacking BLUE Aircraft have Resource Constraints
- ISR/BDA is Imperfect (ISR Errors + Enemy Deception) and Non-Instantaneous



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Air-To-Ground Combat Model
• Additional Features

The way the model is set up, there are a fixed number of attacking aircraft per wave, and they attack a fixed number of "targets", some of which may in fact be False Positives. The model allows BLUE to make an estimate of the extent to which the targets he attacks on any given wave will include False Positives, and to add more targets to his attack list so as to end up attacking the desired number of Positives. At present this estimate is some constant percent, but it could be made to vary from wave to wave depending on some criteria (e.g., how many of the "targets" attacked had defenders that shot back).

In the interest of simplicity, the attrition model is the Lanchester model for directed fire, with appropriate Pk's and firing rates. If BLUE runs out of ammunition he turns around and leaves, and attrition is stopped.

AIR-TO-GROUND COMBAT MODEL

• Additional Features

- Fixed numbers of aircraft per attacking wave
- Each wave attacks some number (i.e., subset) of RED Targets
- Planning/Resource Allocation for each wave based on ISR/BDA following attack by previous wave
- N Defenders per target. Only defenders whose targets are being shot at will shoot back.
- At present, Lanchester attrition model for directed fire is used. Eventually, more sophisticated probabilistic attrition models will be used
- Combat Model uses Pk's and Firing Rates for

  BLUE vs. Fixed RED Targets

  BLUE vs. RED Defenders (different weapons than vs. RED Targets)

  RED Defenders vs. BLUE

- Engagement times may be constrained by weapon-carrying capacity of attacking aircraft

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Examples of Types of Input Parameters

As this chart indicates, this model is really four models in one -- Weapons System, OPS Concept, ISR/BDA, and Scenario. The parameters listed are not all of the parameters, but are the ones that are of most interest.

Examples of Types of Input Parameters

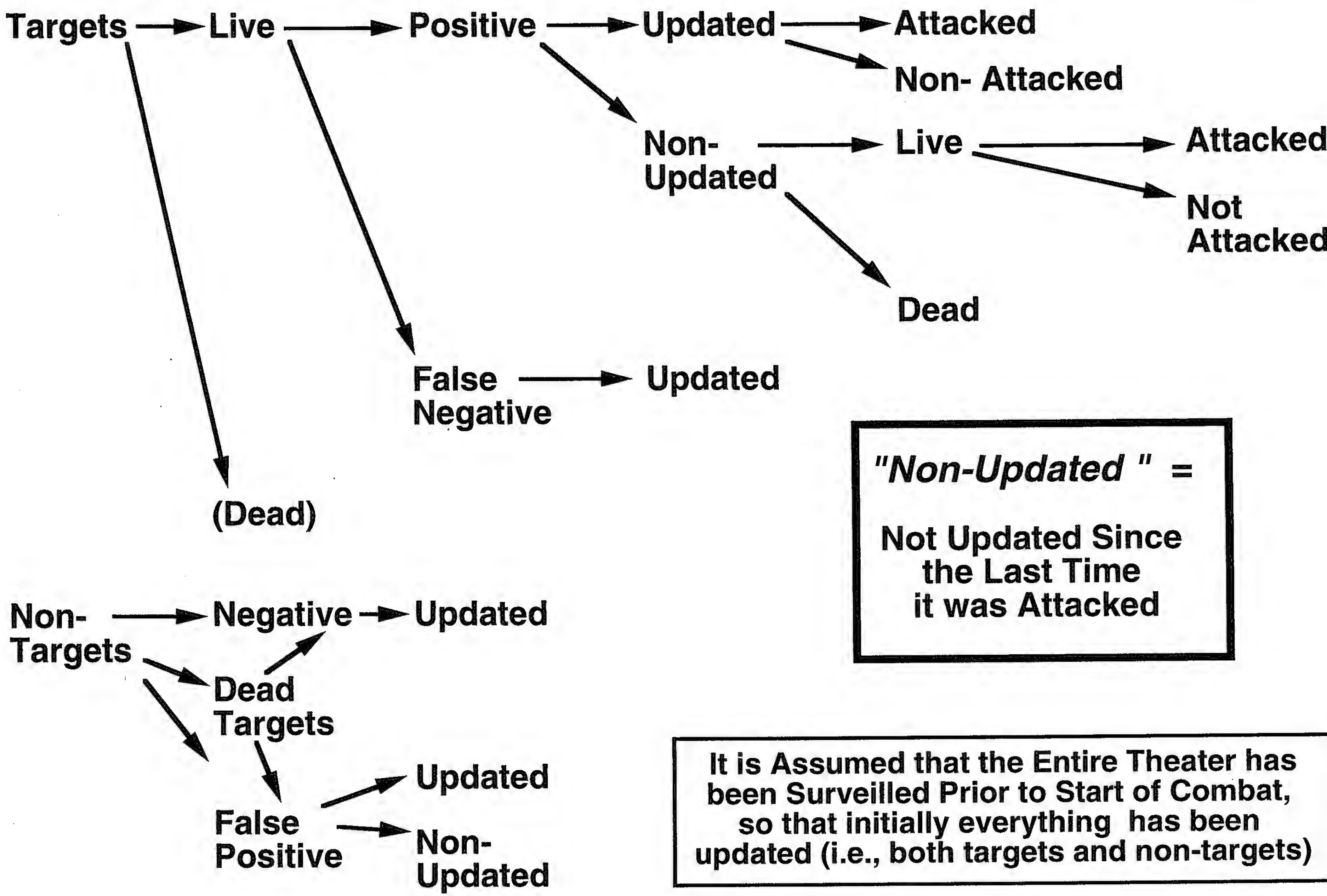
Weapon System	OPS Concept	ISR/BDA	Scenario
• RED & BLUE Pk's	• # A/C per Wave	• Probabilities that - POS mistaken for NEG	• # Targets
• RED & BLUE Firing Rates	• # Targets attacked per wave	- NEG mistaken for POS	• # Non-Targets
• # Weapons per A/C	• Time between successive waves	• ISR Update Rates	• # Defenders per target
Run Control	• Stop if % RED surviving drops below threshhold • Stop if BLUE killed exceeds threshhold		

Decomposition of ISR Target States

One of the key parts of this analysis involves setting up a suitable set of ISR/BDA target states. The need for these states is driven by the need to keep track of what happens during both the attrition and ISR/BDA processes. Thus it is necessary to distinguish first between targets and non-targets; targets may be live or dead (which become non-targets); live targets may be Positives or False Negatives, which in turn may be updated or non-updated; Non-updated Positives may in fact be either live or dead; and for the Positives one has to further distinguish between targets that get attacked during a given wave, and those that don't get attacked. Similarly, the non-targets can be either Negatives or False Positives, either of which may be updated or non-updated. For non-targets it is not necessary to distinguish between Attacked and Non-Attacked, since attacking a non-target will not change its state.

Decomposition of ISR Target States

- *Target States are functions of BLUE perception, ground truth, and recent history*



"Non-Updated " =

Not Updated Since
the Last Time
it was Attacked

It is Assumed that the Entire Theater has been Surveilled Prior to Start of Combat, so that initially everything has been updated (i.e., both targets and non-targets)

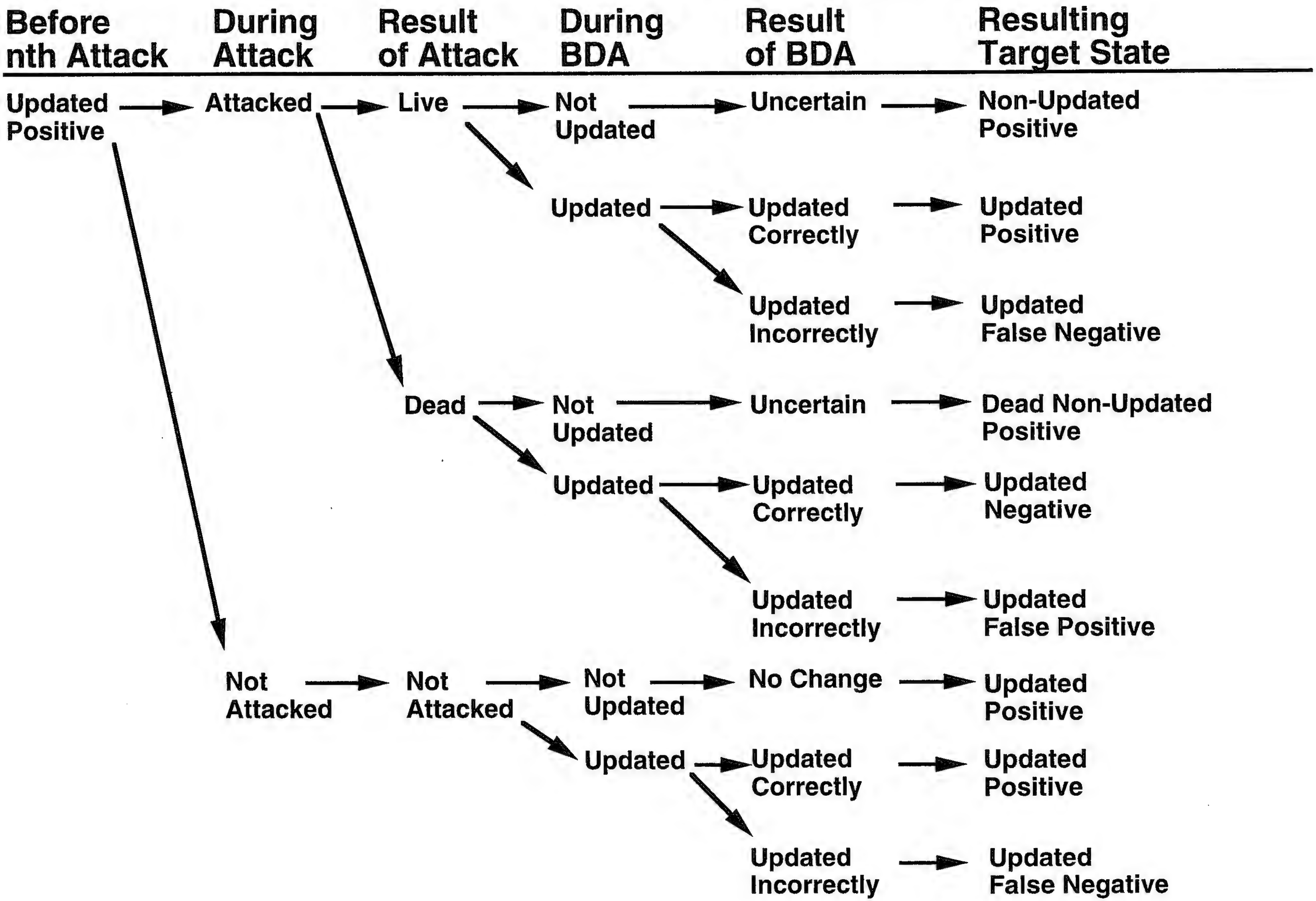
Evolution of ISR Target States
• Example: Updated Positives

To illustrate how this target state decomposition works in practice, consider the example of the Updated Positives. These are Positives that have been attacked, have survived the attack, and have been updated correctly by ISR/BDA as Positives. During the next attack some of there get attacked, and some don't, and as a result, some will be live and some dead after the attack. Prior to the start of the next wave some of these targets (both Attacked and Non-Attacked) will get updated by ISR/BDA, some won't, and of those that get updated, some will get updated correctly and some won't.

The result of all of this is that the Updated Positives will split into a variety of different states -- Updated Negative, Updated False Positive, Dead non-Updated Positive, etc. One needs to go through and do this same kind of analysis for each of the different target state populations, and then re-combine each of the state populations prior to the $(n+1)^{st}$ wave -- i.e., add up all of the Updated Positives, all of the Updated Negatives, and so on, in order to come up with the target state populations prior to the start of the next wave.

Evolution of ISR Target States

• Example: Updated Positives



List of ISR Target States

So the final list of ISR Target states that one ends up with is shown here. As indicated, these states are a combination of ground truth, BLUE perception, and recent history. Targets split into True Positives and False Negatives; the True Positives split further into Updated and Non-Updated. The Updated ones split further into Attacked and Non-Attacked. Non-Updated targets, on the other hand, are targets that have been attacked but not updated by ISR/BDA. Thus they may be either live or dead, and this poses a problem for BLUE, because he doesn't know how may are live, and how many are dead. He may have to waste resource re-attacking dead targets.

Observe that there are no Non-Updated Negatives or False Negatives. This happens because "Non-Updated" applies only to something that has been attacked but not updated since the attack. But by definition it's impossible to attack a Negative. Should BLUE decide to attack a Negative, he would immediately, by his decision to attack it, turn it into a False Positive. Similarly, it is impossible to attack a False Negative. To do so would automatically turn it into a Positive.

List of ISR Target States

- **TARGETS**
  - True ***Positive***
    - **Updated** True ***Positive***
      - **Updated** True ***Positive*** **Attacked**
      - **Updated** True ***Positive*** **Not Attacked**
    - **Non-Updated** True ***Positive***
      - **Non-Updated** True ***Positive*** Live
        - **Non-Updated** True ***Positive*** Live **Attacked**
        - **Non-Updated** True ***Positive*** Live **Not Attacked**
      - **Non-Updated** ***Positive*** Dead
  - False ***Negative***
    - **Updated** False ***Negative***

- **NON-TARGETS**
  - True ***Negative***
    - **Updated** True ***Negative***
  - False ***Positive***
    - **Updated** False ***Positive***
    - **Non-Updated** False ***Positive***

Ground Truth = Outline
BLUE Perception = *Italics*
Recent History = **Bold**

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How Model Is Put Together -- Key Ideas

To illustrate how the target state populations are computed, consider the set of Updated True Positives.

BLUE attacks some number m0 of "targets" (real targets plus non-targets) per wave. Let p1 be the fraction of these attacked "targets" that had been updated prior to the attack. Then the number of these that are Updated **True** Positives is given by (2) -- it's some fraction of m0 p1.

To compute how many of these survive the attack, one needs to subtract off the attrition suffered during the attack.

Of these that survive, some fraction will get updated by BDA prior to the next attack, and of these, some fraction will get updated correctly, becoming part of the population of True Positives prior to the next attack.

How Model is Put Together -- Key Ideas

Example: Start with Updated (True) Positives

Blue Perceptions are in Italics

(1) Assume m_0 *Positives* (Both Updated and Non-Updated) Get Attacked per Wave

Let p_1 = Fraction of Attacked *Positives* That Had Been Updated Prior to the Attack (an OPS Concept Variable)

(2) Then # Updated (True) Positives That Get Attacked

$$= m_0 \, p_1 \frac{(\text{\# Updated Positives})}{(\text{\# Updated Positives} + \text{\# Updated False Positives})}$$

(3) # Of These That Survive Attack = (2) - Attrition of Updated Positives During Attack

(4) Fraction of (3) That Get Updated by BDA Subsequent to Attack =

(3) X Probability of Getting Updated (This Is a Function of BDA Update Rate and Time Between Waves)

(5) Fraction of (4) That Get Updated Correctly =

(4) X Probability of Getting Updated Correctly (an ISR Performance Parameter)

⇒ These Become Updated (True) Positives

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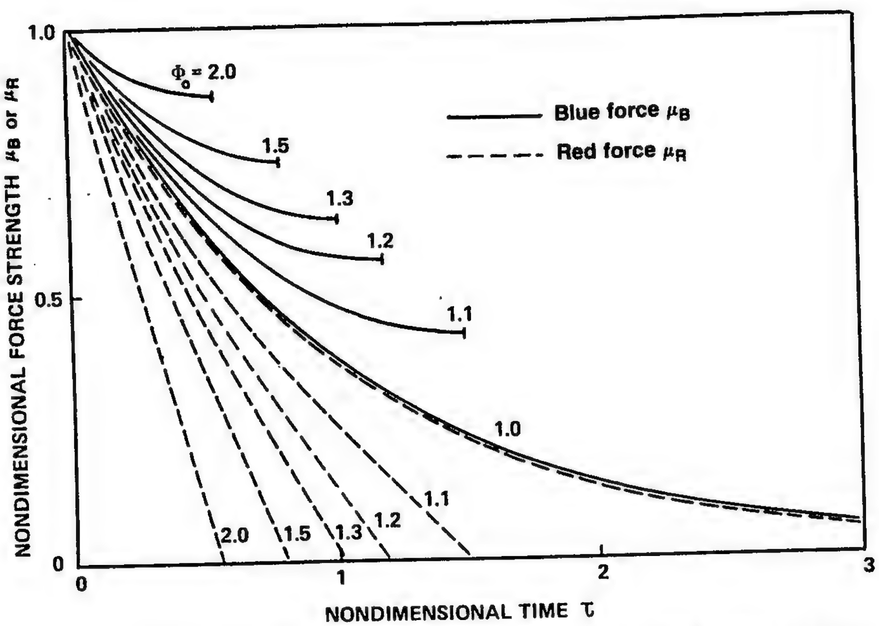
BLUE Superiority Parameter

Before discussing some of the results that come out of this model, it is helpful to understand the role of the superiority parameter in the Lanchester model. The superiority parameter involves the ratio of the force sizes, and the square root of the ratio of the Pk's times the firing rates. The plot shows non-dimensional BLUE and RED force strengths vs. non-dimensional time for different values of the superiority parameter. The greater the BLUE superiority parameter, the shorter the engagement (i.e., the time needed to kill all of the RED), and the fewer the BLUE losses per RED killed. What this means in practice is that an attacker would always try to have enough in the way of force size and firepower so as to ensure an adequate superiority parameter during an engagement.

Observe also that the superiority parameter is linear in brute force (i.e., force size), but goes as the square root of technology (Pk's and firing rates).

BLUE Superiority Parameter

$$\Phi_0 = \frac{\# BLUE}{\# RED} X \sqrt{\frac{BLUE \ P_K \ x \ BLUE \ FIRING \ RATE}{RED \ P_k \ x \ RED \ FIRING \ RATE}}$$



Variation of the nondimensional force strength μ_B (Blue forces) or μ_R (Red forces) with the nondimensional time τ for $\Phi_0 \geq 1$ (directed fire combat).

Lanchester Model

for Directed Fire

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Total BLUE Killed and Total Time Taken vs. Probability that a Negative is Mistaken for a Positive

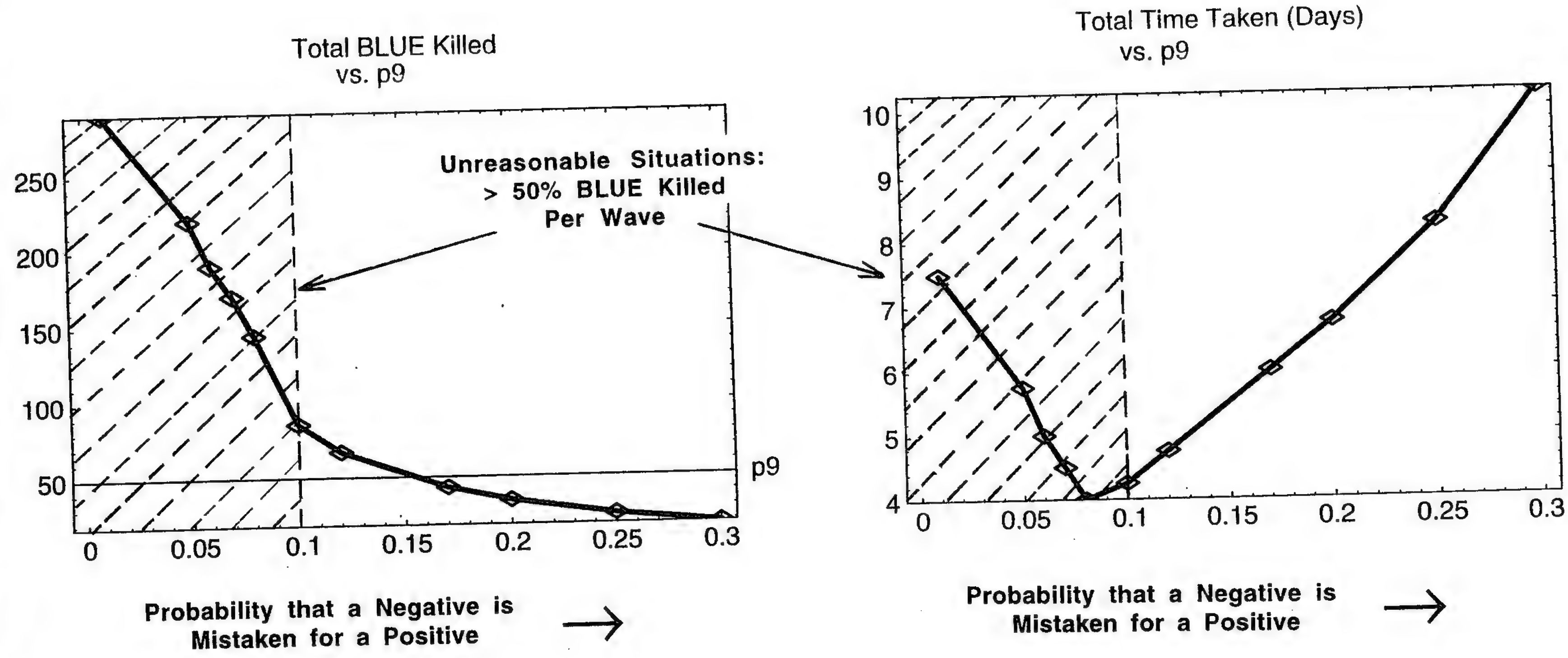
The next three charts show some of the results that illustrate some of the main impacts of ISR/BDA on combat (within the context of the present model!). In viewing these charts, it is very important to understand what was varied and what was held constant. Because this is a parametric model, it is possible to vary each parameter independently, sometimes in ways that would be completely unreasonable from an operational point of view. Even though some of the situations one encounters when doing this are operationally unreasonable, nevertheless they are valuable from the point of view of analysis because of the insights they yield. In practice when one parameter is varied, other parameters would be varied together with it; for example, if more targets are attacked per wave, one would also use more attacking aircraft per wave. These types of operational constraints have, for the most part, been deliberately left out of the model in order to better probe the cause-and effect relationships between the various parameters and outputs. Although this approach does require some mental adjustment on the part of the reader or analyst, it yields insights that might otherwise be missed if other constraints and assumptions were implicitly built into the model.

Recall that the way the model is set up, a fixed number of aircraft attack a fixed number of "targets". What is not fixed, however, is the ratio of real targets to false targets (or non-targets) within this fixed number attacked. The firing rates, Pk's, and force sizes were deliberately set so that if all of the attacked "targets" were in fact real targets, then all of the BLUE attackers would get killed and RED losses would be minimal. This was done intentionally in order to better see the effect of diluting the set of attacked RED targets with False Positives, which would have the effect of shifting the superiority parameter in BLUE's favor.

More specifically, let p9 be the probability that a non-target is mistaken for a real target . Here we had 500 targets and 5000 non-targets, so p9 = 0.1 meant that there were 0.1 x 5000 = 500 false positives, in addition to the 500 real targets. As p9 increases, the ratio of real targets to false positives decreases, so in any attack against a fixed number of "targets" there will be progressively fewer real targets attacked. Thus the BLUE/RED force ratio will be greater, and there will be fewer BLUE losses per RED killed, hence the total BLUE killed will decrease as p9 increases.

On the other hand, the total time taken for BLUE to accomplish its objective has a minimum near p9 = 0.1. The reason for this is as follows: For small values of p9 BLUE is out gunned and all BLUE are killed on every wave. As p9 initial increases BLUE is still out gunned, but not quite as badly, and is able to kill more of RED on each wave, before getting wiped out by RED. As p9 is increased yet further, the percentage of real targets attacked in each wave gets diluted further, until eventually BLUE is no longer out gunned. At this point BLUE is able to start killing all of the RED targets it attacks in each wave. But as the percentage of RED targets attacked in each wave decreases (due to increasing p9), it takes more waves in order for BLUE to accomplish its objective.

Total BLUE Killed and Total Time Taken vs. Probability that a Negative is Mistaken for a Positive



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Total Blue Killed and Total Time Taken vs. BLUE's Estimate of the Fractional Increase Needed in Number of "Targets" Attacked to Ensure that the Desired Number of Real Targets get Attacked

epsFP0 is BLUE's estimate of the fractional increase needed in the number of "targets" attacked to ensure that out of the total number of "targets" attacked, the desired number of them will be real targets.

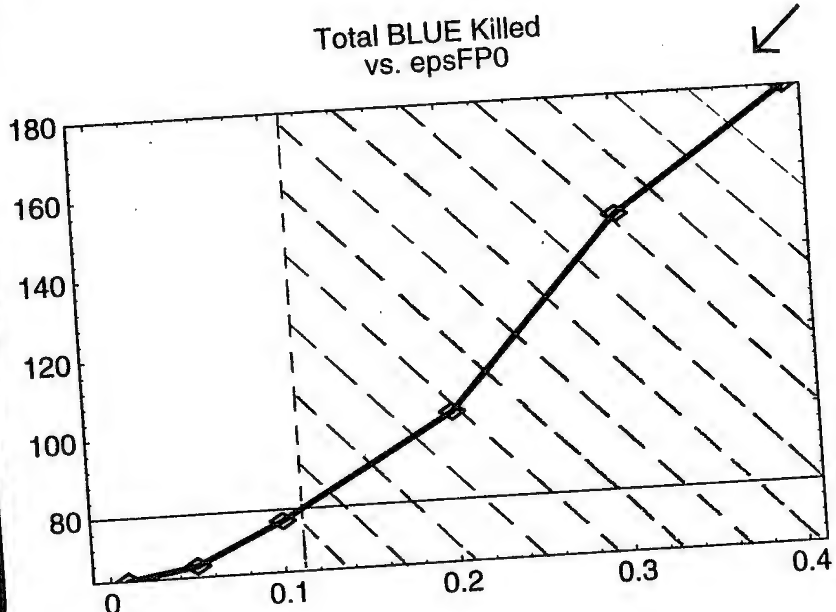
For a fixed ratio of real targets to False Positives, as epsFP0 is increased, more and more real targets will be attacked per wave, hence BLUE losses will increase with epsFP0.

On the other hand, when epsFP0 is small, a relatively small number of real targets will be attacked per wave, and more waves will be required for BLUE to achieve its objective.

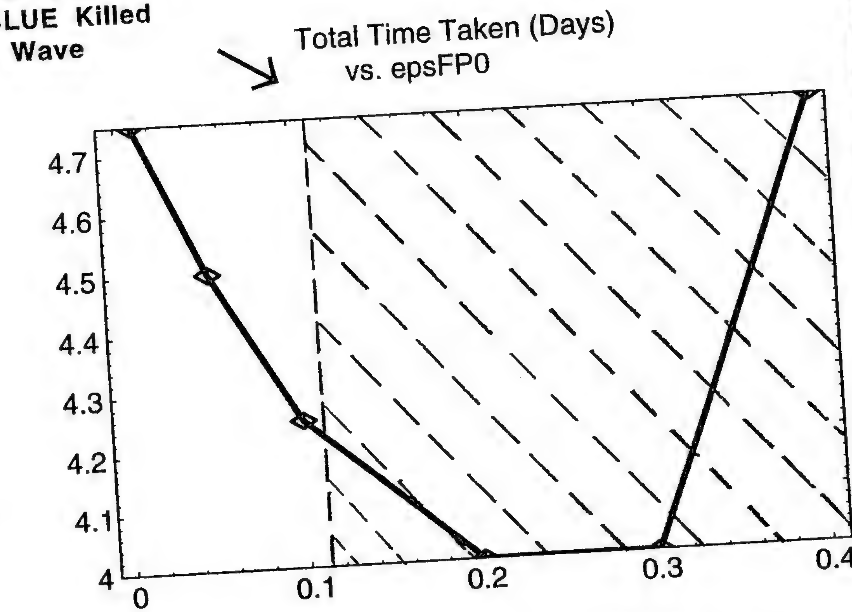
As epsFP0 is increased, BLUE encounters more real targets per wave, and so the total time required decreases. Eventually, however, BLUE gets to the point of having to take on too many real targets per wave, with the result that BLUE losses per wave become very high, while RED losses per wave decrease. When this starts to happen, the total time taken becomes an increasing function of epsFP0.

Total BLUE Killed and Total Time Taken vs. BLUE's Estimate of the Fractional Increase Needed in Number of "Targets" Attacked to Ensure that the Desired Number of Real Targets get Attacked

Unreasonable Situations:
> 50% BLUE Killed
Per Wave



Estimate of the Fractional Increase Needed
in Number of "Targets" Attacked



Estimate of the Fractional Increase Needed
in Number of "Targets" Attacked

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Total Blue Killed and Total Time Taken vs. Time Between Waves

When the target attack rate (i.e., number of targets attacked per wave divided by the time between waves) is greater than the ISR/BDA target update rate, in other words, when the time between waves is very short, eventually BLUE will run out of updated targets to attack (recall that initially everything has been updated), and will have to attack mostly non-updated (hence possibly dead) targets, plus the few positives that get updated between waves, resulting in a more dilute "target" set, and fewer BLUE losses. For the parameters used here, the target attack rate exceeds the target update rate once the time between waves drops below about four hours.

Once the target attack rate slows down to the point where it's less than or equal to the ISR/BDA update rate, then we get a "richer" target set because enough targets are getting updated between waves for BLUE to avoid attacking too many non-updated targets. But since the number of attacking aircraft is being held fixed, this has the effect of decreasing BLUE's superiority parameter, thus increasing BLUE losses per target attacked, which leads to more total BLUE losses.

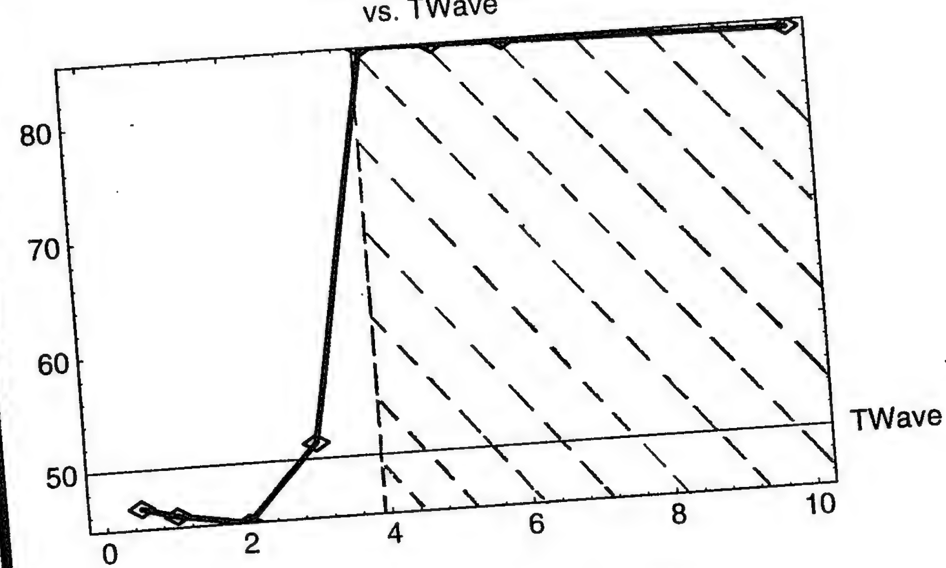
On the other hand, the total time taken is a more or less linear function of the time between waves because it equals the number of waves times the time between waves. When the time between waves is very short, BLUE ends up attacking a more dilute "target" set, as discussed above, which means that it takes relatively more waves for BLUE to accomplish its goal. Once the time between waves is long enough so that the target attack rate no longer exceeds the ISR BDA target update rate, then total BLUE killed drops slightly with the time between waves. This happens because more and more of the attacked targets are getting updated (and confirmed as killed or live) between waves, which means that more dead targets are getting confirmed as dead, which in turn means that the pool of False Negatives increases more slowly.

Observe also that a fast OPS Tempo (for example, one to two hours between waves) leads to less BLUE losses and less time taken, even though each attack is less efficient. As mentioned above, the time between waves has a potent multiplicative effect on the total time taken. The slight increase in total BLUE killed as the time between waves drops below two hours is an artifact of the model: the model only checks total RED killed at the end of each wave, and thus it is possible for it to "overshoot" its goal slightly if it was a fraction of a percent short of 50% RED killed on the previous wave. But more RED killed also means more BLUE killed.

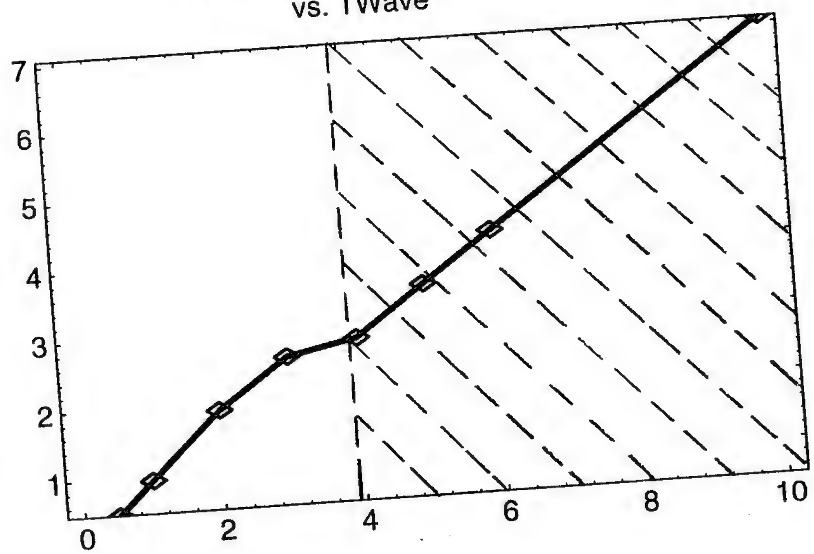
Total BLUE Killed and Total Time Taken vs. Time Between Waves

Unreasonable Situations:
> 50% BLUE Killed
Per Wave

Total BLUE Killed
vs. TWave



Total Time Taken (Days)
vs. TWave



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Impact of ISR/BDA on Distribution of Target States

As indicated on the chart, there are various ways in which imperfect ISR/BDA can increase the number of False Positives. It can also make it harder to find the True Positives, and it can cause dead targets to get attacked again. The ratio of Positives to False Positives will always decrease with time due to RED attrition plus the probability of updating a dead target to a positive, but the better the ISR/BDA capability, the slower this ratio will decrease.

Impacts of ISR/BDA on Distribution of Target States

- BLUE's list of Positives may include an increasing number of False Positives due to
  - Increased Probability of mistaking a Negative for a Positive (especially if many Negatives are present)
  - Increased Probability of mistaking a dead target for a live one
  - High ISR/BDA update rate (more dead targets updated per unit time -- some will be updated to Positives)
- Positives can be harder to find due to increased probability of mistaking a Positive for a Negative
- Dead Targets (that have been previously attacked) get attacked again if
  - Time between waves is too short
  - Update rate is too slow
- Ratio of Positives to False Positives decreases with time due to RED attrition plus probability of dead targets being updated to Positives

Operational Impacts of Imperfect ISR/BDA

In order to cope with the uncertainties produced by the presence of False Positives, BLUE needs to "pad" his superiority parameter in either of two ways: (a) attack fewer targets per wave, which is equivalent to trading losses vs. total time, or (b) add more resources to each wave.

Increasing the OPS Tempo has a generally positive effect, as noted.

And even though the superiority parameter is linear in brute force, while it goes as the square root of technology, technology may be less expensive, especially when one considers the potential "costs" of casualties, POWs, and hostage situations.

Operational Impacts of Imperfect ISR/BDA

- In planning an attack, BLUE wants a reasonable superiority parameter
  - If BLUE underestimates RED False Positives (including dead targets) he will use more resources than necessary
  - If BLUE overestimates RED False Positives, he will be outgunned

- BLUE can achieve a reasonable superiority parameter in two ways:
  - By attacking fewer targets per wave (with same number of attackers) => fewer losses but more total time required (trade losses vs. time)
  - To be on the safe side BLUE can "pad" superiority parameter by adding more resources to each wave -- wasteful but safer

- Increased OPS tempo (time between waves) without increased BDA update rate may still pay off (despite inefficient operation -- more False Positives attacked) because both casualties and total time taken are less

- Brute force (more A/C, faster OPS tempo, fewer targets attacked per wave) has more impact on "padding" the superiority parameter than technology (Pk's, firing rates). Superiority parameter is linear in brute force, but goes as square root of technology. But technology may be less expensive.

Utility of Improved ISR/BDA

As noted, improved ISR/BDA can (a) reduce the resources required to accomplish a mission, (b) reduce the time and associated cost of accomplishing a mission, (c) reduce the technology requirements (associated with a technology solution to increasing the superiority parameter) to the point where the technology solution becomes feasible.

Utility of Improved ISR/BDA

- More efficient use of BLUE resources. Less "pad" needed per wave to ensure adequate BLUE superiority parameter.
  => Do same job with fewer resources

- Gives BLUE more flexibility to trade brute force for technology
  => Technology solution may be cheaper

- Reduces total time taken to accomplish BLUE objective
  => Less total expense

- Improves efficiency of fast OPS Tempo, and permits yet faster OPS Tempo
  => Less total time taken => Less total expense

- In actual practice there may be a variety of operational constraints that limit the extent to which BLUE can take advantage of improved ISR/BDA

Lessons Learned

This turned out to be a very complex problem, mainly because of the non-trivial target state structure, coupled with the nonlinearities produced by the inclusion of both BLUE perceptions together with Ground Truth in estimating expected values. Despite these difficulties, it was possible to get a considerable amount of insight into the underlying cause-and-effect mechanisms, with some surprising conclusions (which, of course, should be interpreted in the light of the simple assumptions used). As an exploratory model, it provides a good indication of the challenges that can be expected with more complex models. And it is clear that the target state structure is something that needs to be analyzed very carefully when other aspects of ISR performance (such as target position, target velocity, position and velocity uncertainties, age of data, target tracking, IFF, assessing target intent, and so on) are taken into account.

On the other hand, it's not clear that the above-mentioned nonlinearities would necessarily play the same role in a probabilistic analysis of the problem, since in the latter case one is attempting to compute distributions of outcomes, rather than expected values. This is something that requires further research and analysis.

Lessons Learned

- Seemingly simple problem turned out to be very complex, with many subtleties
- BLUE perception vs. Ground Truth in computing Expected Values is source of considerable non-linearity
- Target states need to include Blue Perception, Ground Truth, plus some recent history
- Complexity of target state structure drives complexity of analysis
- Expressions for target state populations are algebraically complex, non-linear, and opaque
- Nevertheless, chains of cause-and-effect can be inferred, leading to some unexpected conclusions
- Conclusions driven largely by simple assumptions used, i.e., Directed Fire Lanchester Model, Fixed Targets, and True/False Positive/Negative Target States.
- Some conclusions may extrapolate to more complex situations, others probably won't.

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